



On the gauge-invariant operator A_{\min}^2 in Euclidean Yang-Mills theories

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Abstract

We review our recent work on the gauge-invariant non-local dimension-two operator A_{\min}^2 , whose minimization is defined along the gauge orbit. Albeit non-local, the operator A_{\min}^2 can be cast in local form through the introduction of an auxiliary Stueckelberg field. The whole procedure results into a local action which turns out to be renormalizable to all orders.

1. Introduction

The study of operators of dimension two in Yang-Mills theories has already a relatively long history, as confirmed by the considerable amount of results obtained through theoretical and phenomenological studies as well as from lattice simulations [1–24, 26, 27, 27–35].

In particular, the dimension two gluon condensate $\langle A_{\mu}^a A_{\mu}^a \rangle$ has been much investigated in the Landau gauge. According to [5], this condensate enters the operator product expansion (OPE) of the gluon propagator. A combined OPE and lattice analysis has shown that this condensate can account for the $1/Q^2$ corrections which have been reported [18–21, 24, 27–31, 33–35] in the running of the coupling constant and in the gluon correlation functions.

An effective potential for $\langle A_{\mu}^a A_{\mu}^a \rangle$ in Landau gauge has been obtained and evaluated in analytic form at two loops in [7, 10, 11, 15, 16], showing that a nonvanishing value of $\langle A_{\mu}^a A_{\mu}^a \rangle$ is favoured as it lowers the vacuum energy. As a consequence, a dynamical gluon mass is generated. We point out that, in the Landau gauge, the operator $A_{\mu}^a A_{\mu}^a$ turns out to be *BRS*-invariant on shell, a property which has allowed for an all-orders proof of its multiplicative renormalizability [36, 37].

Dimension-two condensates also play an important role within the context of the Gribov-Zwanziger approach to confinement [38–42] as well as for the formation of a dynamical gluon mass within the framework of the Dyson-Schwinger equations in Landau gauge, as reported in [1, 43, 44]. These non-perturbative effects give rise to the so called decoupling solution for the gluon propagator [1, 38–40, 43, 45], *i.e.* to a propagator which exhibits positivity violation, while attaining a finite non-vanishing value at zero momentum. Until now, this behaviour is in very good agreement with the most recent lattice numerical simulations [46–49]. The generalization of these results to the linear covariant gauges has been worked out recently and can be found in [50–59].

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Even if a large amount of results has been obtained, many aspects related to dimension-two operators require further investigation as, for instance, the issue of the gauge invariance, a topic of pivotal importance in order to give a precise physical meaning to the corresponding condensates. This is precisely the aspect which has been addressed recently in [60] and which will be reviewed in the present contribution.

2. The gauge invariant operator A_{\min}^2

A genuine gauge-invariant dimension-two operator A_{\min}^2 can be constructed by minimizing the functional $\text{Tr} \int d^4x A_\mu^u A_\mu^u$ along the gauge orbit of A_μ , see [60] and refs. therein, namely

$$\begin{aligned} A_{\min}^2 &\equiv \min_{\{u\}} \text{Tr} \frac{1}{2} \int d^4x A_\mu^u A_\mu^u, \\ A_\mu^u &= u^\dagger A_\mu u + \frac{i}{g} u^\dagger \partial_\mu u. \end{aligned} \quad (1)$$

In particular, the stationary condition of the functional (1) gives rise to a non-local transverse field configuration A_μ^h , $\partial_\mu A_\mu^h = 0$, which can be expressed as an infinite series in the gauge field A_μ [60], *i.e.*

$$\begin{aligned} A_\mu^h &= \mathcal{P}_{\mu\nu} \left(A_\nu - ig \left[\frac{1}{\partial^2} \partial A, A_\nu \right] \right. \\ &\quad \left. + \frac{ig}{2} \left[\frac{1}{\partial^2} \partial A, \partial_\nu \frac{1}{\partial^2} \partial A \right] \right) + O(A^3) \end{aligned} \quad (2)$$

where $\mathcal{P}_{\mu\nu} = (\delta_{\mu\nu} - \frac{\partial_\mu \partial_\nu}{\partial^2})$ is the transverse projector. The configuration A_μ^h turns out to be left invariant by infinitesimal gauge transformations order by order in the gauge coupling g [61]

$$\delta A_\mu^h = 0, \quad \delta A_\mu = -\partial_\mu \omega + ig [A_\mu, \omega]. \quad (3)$$

The gauge-invariant nature of expression (1) can be made manifest by rewriting it in terms of the field strength $F_{\mu\nu}$. In fact, it turns out that [62]

$$\begin{aligned} A_{\min}^2 &= \frac{1}{2} \text{Tr} \int d^4x A_\mu^h A_\mu^h = -\frac{1}{2} \text{Tr} \int d^4x \left(F_{\mu\nu} \frac{1}{D^2} F_{\mu\nu} \right. \\ &\quad \left. + 2i \frac{1}{D^2} F_{\lambda\mu} \left[\frac{1}{D^2} D_\kappa F_{\kappa\lambda}, \frac{1}{D^2} D_\nu F_{\nu\mu} \right] \right. \\ &\quad \left. - 2i \frac{1}{D^2} F_{\lambda\mu} \left[\frac{1}{D^2} D_\kappa F_{\kappa\nu}, \frac{1}{D^2} D_\nu F_{\lambda\mu} \right] \right) + O(F^4) \end{aligned}$$

where the operator $(D^2)^{-1}$ denotes the inverse of the Laplacian $D^2 = D_\mu D_\mu$ with D_μ being the covariant derivative [62]. Let us also notice that, in the particular

case of the Landau gauge $\partial_\mu A_\mu = 0$, the gauge invariant quantity $(A_\mu^h A_\mu^h)$ reduces to the operator A^2

$$(A_\mu^{h,a} A_\mu^{h,a}) \Big|_{\text{Landau}} = A_\mu^a A_\mu^a. \quad (4)$$

3. Construction of a local Lagrangian for A_{\min}^2

In order to construct a local action, we start with the standard Faddeev-Popov action of Yang-Mills theory quantized in linear covariant gauges with the inclusion of the non-local gauge invariant operator $(A_\mu^h A_\mu^h)$ as well as of a constraint enforcing the transversality of the field configuration A_μ^h , *i.e.* we consider the action

$$S = S_{FP} + \int d^4x \left(\tau^a \partial_\mu A_\mu^{h,a} + \frac{m^2}{2} A_\mu^{h,a} A_\mu^{h,a} \right) \quad (5)$$

where S_{FP} stands for the Faddeev-Popov action in linear covariant gauges

$$S_{FP} = \int d^4x \left(\frac{1}{4} F_{\mu\nu}^a F_{\mu\nu}^a + \frac{\alpha}{2} b^a b^a + i b^a \partial_\mu A_\mu^a + \bar{c}^a \partial_\mu D_\mu^{ab} c^b \right)$$

and where we have introduced the operator $(A_\mu^h A_\mu^h)$ through the mass parameter m^2 . Also, the transversality of A_μ^h is enforced by the Lagrange multiplier τ^a .

The action (5) is still non-local, since the expression for $(A_\mu^h A_\mu^h)$ is an infinite sum of nonlocal terms. Nevertheless, expression (5) can be cast in local form [60] by means of the introduction of an auxiliary localizing Stueckelberg field ξ^a , whose role is to give, for each gauge field A_μ , its corresponding configuration that minimizes the functional A^2 , *i.e.*, A_μ^h . This is most naturally implemented by defining a field h which effectively acts on A_μ as a gauge transformation would act, in order to provide the minimizing configuration A_μ^h , that is,

$$A_\mu^h \equiv A_\mu^{h,a} T^a = h^\dagger A_\mu h + \frac{i}{g} h^\dagger \partial_\mu h. \quad (6)$$

with

$$h = e^{ig\xi} = e^{ig\xi^a T^a}, \quad (7)$$

where $\{T^a\}$ are the generators of the gauge group $SU(N)$ and ξ^a is a Stueckelberg field.

Thus, by substituting the expression (6) for A_μ^h in the action (5), we now have a local theory in terms of the field ξ . The price one has to pay to have such a local theory is a non-polynomial action. Indeed, by

expanding (6), one finds an infinite series whose first terms are

$$(A^h)_\mu^a = A_\mu^a - D_\mu^{ab} \xi^b - \frac{g}{2} f^{abc} \xi^b D_\mu^{cd} \xi^d + O(\xi^3), \quad (8)$$

where

$$D_\mu^{ab} = \delta^{ab} \partial_\mu - g f^{abc} A_\mu^c \quad (9)$$

is the covariant derivative in the adjoint representation.

The nonlocal expression (2) for A_μ^h in terms of the gauge field A_μ can be recovered by imposing the transversality condition $\partial_\mu A_\mu^h = 0$, *i.e.* after taking the divergence of both sides of (8), equating it to zero and solving for the Stueckelberg field ξ^a [54, 55, 60]. Due to the transversality condition enforced by the Lagrange multiplier τ^a , the Stueckelberg field ξ^a acquires now a specific meaning: it is precisely the field which brings a generic gauge configuration A_μ into the gauge-invariant and transverse field configuration A_μ^h which minimizes the functional A_{min}^2 . As shown in [60], this feature, encoded in the term $\int d^4x \tau^a \partial_\mu A_\mu^{h,a}$, gives rise to deep differences between our construction and the standard Stueckelberg mass term, which is known to be a non-renormalizable theory which has to be treated as an effective field theory [63].

An important property of A_μ^h , as defined by eq.(6), is its gauge invariance, that is,

$$A_\mu^h \rightarrow A_\mu^h, \quad (10)$$

as can be seen from the gauge transformations with $SU(N)$ matrix V

$$A_\mu \rightarrow V^\dagger A_\mu V + \frac{i}{g} V^\dagger \partial_\mu V, \quad h \rightarrow V^\dagger h$$

The local version of the action (5), in terms of the Stueckelberg field ξ^a , is thus given by

$$\begin{aligned} S &= S_{FP} + \int d^4x \left(\tau^a \partial_\mu A_\mu^{h,a} + \frac{m^2}{2} A_\mu^{h,a} A_\mu^{h,a} \right) \\ &= S_{FP} + \int d^4x \left[\tau^a (A_\mu^a - D_\mu^{ab} \xi^b) \right] \\ &\quad + \frac{m^2}{2} \int d^4x (A_\mu^a - D_\mu^{ab} \xi^b) (A_\mu^a - D_\mu^{ae} \xi^e) \\ &\quad + \dots \end{aligned} \quad (11)$$

Due to the use of the auxiliary Stueckelberg field ξ^a , expression (11) exhibits a non-polynomial character.

3.1. BRST invariance

The local action S enjoys an exact BRST symmetry [60]:

$$sS = 0, \quad (12)$$

where the nilpotent BRST transformations are given by

$$\begin{aligned} sA_\mu^a &= -D_\mu^{ab} c^b, \\ sc^a &= \frac{g}{2} f^{abc} c^b c^c, \\ s\bar{c}^a &= ib^a, \\ sb^a &= 0, \\ s\tau^a &= 0, \\ s^2 &= 0. \end{aligned} \quad (13)$$

From [64], for the Stueckelberg field we have, with i, j indices associated with a generic representation,

$$sh^{ij} = -igc^a (T^a)^{ik} h^{kj}, \quad s(A^h)_\mu^a = 0, \quad (14)$$

from which the BRST transformation of the field ξ^a can be evaluated iteratively, yielding

$$s\xi^a = -c^a + \frac{g}{2} f^{abc} c^b \xi^c - \frac{g^2}{12} f^{amr} f^{mpq} c^p \xi^q \xi^r + O(\xi^3)$$

As shown in [60], the BRST invariance of the action S , eq.(5), can be translated into functional identities which can be used to show that S is in fact renormalizable to all orders of perturbation theory.

4. Conclusion

A gauge invariant dimension two operator can be introduced by minimizing the functional $\text{Tr} \int d^4x A_\mu^h A_\mu^h$ along the gauge orbit, *i.e.*

$$A_{min}^2 = \frac{1}{2} \text{Tr} \int d^4x A_\mu^h A_\mu^h, \quad (15)$$

with A_μ^h the transverse configuration, $\partial_\mu A_\mu^h = 0$, given in expression (2).

Despite the highly non-local character, a fully local set up for both operators $(A_\mu^h A_\mu^h)$ and A_μ^h can be constructed, giving rise to a local and BRST-invariant action S , eq.(5), which turns out to be renormalizable to all orders of perturbation theory [60]. Let us conclude by mentioning that, owing to the gauge invariance of $(A_\mu^h A_\mu^h)$ and A_μ^h , the corresponding anomalous dimensions, $(\gamma_{(A^h)^2}, \gamma_{A^h})$, turn out to be independent from the

gauge parameter α entering the gauge fixing condition, being given by [60]

$$\begin{aligned}\gamma_{(A^h)^2} &= \gamma_{A^2} \Big|_{\text{Landau}} = - \left(\frac{\beta(a)}{a} + \gamma_A^{\text{Landau}}(a) \right) \\ \gamma_{A^h} &= \gamma_{A^h} \Big|_{\alpha=0} = \gamma_A^{\text{Landau}}(a) \\ a &= \frac{g^2}{16\pi^2}\end{aligned}\quad (16)$$

where $(\beta(a), \gamma_A^{\text{Landau}}(a))$ denote, respectively, the β -function and the anomalous dimension of the gauge field A_μ in the Landau gauge, corresponding to set the gauge parameter α to zero, $\alpha = 0$. One sees therefore that $(\gamma_{(A^h)^2}, \gamma_{A^h})$ are not independent parameters of the theory.

References

- [1] J. M. Cornwall, Phys. Rev. D **26**, 1453 (1982).
- [2] J. Greensite and M. B. Halpern, Nucl. Phys. B **271**, 379 (1986).
- [3] M. Stingl, Phys. Rev. D **34**, 3863 (1986) [Erratum-ibid. D **36**, 651 (1987)].
- [4] M. J. Lavelle and M. Schaden, Phys. Lett. B **208**, 297 (1988).
- [5] F. V. Gubarev and V. I. Zakharov, Phys. Lett. B **501**, 28 (2001) [arXiv:hep-ph/0010096].
- [6] F. V. Gubarev, L. Stodolsky and V. I. Zakharov, Phys. Rev. Lett. **86**, 2220 (2001) [arXiv:hep-ph/0010057].
- [7] H. Verschelde, K. Knecht, K. Van Acoleyen and M. Vanderkeken, Phys. Lett. B **516**, 307 (2001) [arXiv:hep-th/0105018].
- [8] K. I. Kondo, Phys. Lett. B **514**, 335 (2001) [arXiv:hep-th/0105299].
- [9] K. I. Kondo, T. Murakami, T. Shinohara and T. Imai, Phys. Rev. D **65**, 085034 (2002) [arXiv:hep-th/0111256].
- [10] D. Dudal, H. Verschelde, R. E. Browne and J. A. Gracey, Phys. Lett. B **562**, 87 (2003) [arXiv:hep-th/0302128].
- [11] R. E. Browne and J. A. Gracey, JHEP **0311**, 029 (2003) [arXiv:hep-th/0306200].
- [12] D. Dudal, H. Verschelde, V. E. R. Lemes, M. S. Sarandy, S. P. Sorella and M. Picariello, Annals Phys. **308**, 62 (2003) [arXiv:hep-th/0302168].
- [13] D. Dudal, H. Verschelde, J. A. Gracey, V. E. R. Lemes, M. S. Sarandy, R. F. Sobreiro and S. P. Sorella, JHEP **0401**, 044 (2004) [arXiv:hep-th/0311194].
- [14] D. Dudal, J. A. Gracey, V. E. R. Lemes, M. S. Sarandy, R. F. Sobreiro, S. P. Sorella and H. Verschelde, Phys. Rev. D **70**, 114038 (2004) [arXiv:hep-th/0406132].
- [15] R. E. Browne and J. A. Gracey, Phys. Lett. B **597**, 368 (2004) [arXiv:hep-ph/0407238].
- [16] J. A. Gracey, Eur. Phys. J. C **39**, 61 (2005) [arXiv:hep-ph/0411169].
- [17] X. d. Li and C. M. Shakin, Phys. Rev. D **71**, 074007 (2005) [arXiv:hep-ph/0410404].
- [18] P. Boucaud, A. Le Yaouanc, J. P. Leroy, J. Micheli, O. Pene and J. Rodriguez-Quintero, Phys. Rev. D **63**, 114003 (2001) [arXiv:hep-ph/0101302].
- [19] P. Boucaud, J. P. Leroy, A. Le Yaouanc, J. Micheli, O. Pene, F. De Soto, A. Donini, H. Moutare and J. Rodriguez-Quintero, Phys. Rev. D **66**, 034504 (2002) [arXiv:hep-ph/0203119].
- [20] P. Boucaud, F. de Soto, J. P. Leroy, A. Le Yaouanc, J. Micheli, H. Moutarde, O. Pene and J. Rodriguez-Quintero, arXiv:hep-lat/0504017.
- [21] E. Ruiz Arriola, P. O. Bowman and W. Broniowski, Phys. Rev. D **70**, 097505 (2004) [arXiv:hep-ph/0408309].
- [22] T. Suzuki, K. Ishiguro, Y. Mori and T. Sekido, Phys. Rev. Lett. **94**, 132001 (2005) [arXiv:hep-lat/0410001].
- [23] F. V. Gubarev and S. M. Morozov, Phys. Rev. D **71**, 114514 (2005) [arXiv:hep-lat/0503023].
- [24] S. Furui and H. Nakajima, Hideo, Few Body Syst. **40**, 101-128 (2006) [arXiv:hep-lat/0503029].
- [25] P. Boucaud, J. P. Leroy, A. Le Yaouanc, A. Y. Lokhov, J. Micheli, O. Pene, J. Rodriguez-Quintero and C. Roiesnel, arXiv:hep-lat/0507005.
- [26] M. N. Chernodub, K. Ishiguro, Y. Mori, Y. Nakamura, M. I. Polikarpov, T. Sekido, T. Suzuki and V. I. Zakharov, arXiv:hep-lat/0508004.
- [27] P. Boucaud, J. P. Leroy, A. Le Yaouanc, A. Y. Lokhov, J. Micheli, O. Pene, J. Rodriguez-Quintero and C. Roiesnel, JHEP **0601**, 037 (2006) doi:10.1088/1126-6708/2006/01/037 [hep-lat/0507005].
- [28] P. Boucaud, F. De Soto, J. P. Leroy, A. Le Yaouanc, J. Micheli, O. Pene and J. Rodriguez-Quintero, Phys. Rev. D **79**, 014508 (2009) doi:10.1103/PhysRevD.79.014508 [arXiv:0811.2059 [hep-ph]].
- [29] O. Pene *et al.*, PoS FACESQCD , 010 (2010) [arXiv:1102.1535 [hep-lat]].
- [30] P. Boucaud, M. E. Gomez, J. P. Leroy, A. Le Yaouanc, J. Micheli, O. Pene and J. Rodriguez-Quintero, Phys. Rev. D **82**, 054007 (2010) doi:10.1103/PhysRevD.82.054007 [arXiv:1004.4135 [hep-ph]].
- [31] B. Blossier *et al.* [ETM Collaboration], Phys. Rev. D **82**, 034510 (2010) doi:10.1103/PhysRevD.82.034510 [arXiv:1005.5290 [hep-lat]].
- [32] D. Dudal, O. Oliveira and N. Vandersickel, Phys. Rev. D **81**, 074505 (2010) doi:10.1103/PhysRevD.81.074505 [arXiv:1002.2374 [hep-lat]].
- [33] P. Boucaud, D. Dudal, J. P. Leroy, O. Pene and J. Rodriguez-Quintero, JHEP **1112**, 018 (2011) doi:10.1007/JHEP12(2011)018 [arXiv:1109.3803 [hep-ph]].
- [34] B. Blossier *et al.*, Phys. Rev. D **85**, 034503 (2012) doi:10.1103/PhysRevD.85.034503 [arXiv:1110.5829 [hep-lat]].
- [35] B. Blossier, P. Boucaud, M. Brinet, F. De Soto, V. Morenas, O. Pene, K. Petrov and J. Rodriguez-Quintero, Phys. Rev. D **87**, 074033 (2013) doi:10.1103/PhysRevD.87.074033 [arXiv:1301.7593 [hep-ph]].
- [36] D. Dudal, H. Verschelde and S. P. Sorella, Phys. Lett. B **555**, 126 (2003) [arXiv:hep-th/0212182].
- [37] J. A. Gracey, Phys. Lett. B **552** (2003) 101 [arXiv:hep-th/0211144].
- [38] D. Dudal, R. F. Sobreiro, S. P. Sorella and H. Verschelde, Phys. Rev. D **72**, 014016 (2005) [arXiv:hep-th/0502183].
- [39] D. Dudal, S. P. Sorella, N. Vandersickel and H. Verschelde, Phys. Rev. D **77**, 071501 (2008) doi:10.1103/PhysRevD.77.071501 [arXiv:0711.4496 [hep-th]].
- [40] D. Dudal, J. A. Gracey, S. P. Sorella, N. Vandersickel and H. Verschelde, Phys. Rev. D **78** (2008) 065047 doi:10.1103/PhysRevD.78.065047 [arXiv:0806.4348 [hep-th]].
- [41] D. Dudal, S. P. Sorella and N. Vandersickel, Phys. Rev. D **84**, 065039 (2011) doi:10.1103/PhysRevD.84.065039 [arXiv:1105.3371 [hep-th]].
- [42] N. Vandersickel and D. Zwanziger, Phys. Rept. **520** (2012) 175 doi:10.1016/j.physrep.2012.07.003 [arXiv:1202.1491 [hep-th]].
- [43] A. C. Aguilar, D. Binosi and J. Papavassiliou, Phys.

- Rev. D **78** (2008) 025010 doi:10.1103/PhysRevD.78.025010 [arXiv:0802.1870 [hep-ph]].
- [44] A. C. Aguilar, D. Binosi and J. Papavassiliou, Front. Phys. China **11** (2016) no.2, 111203 doi:10.1007/s11467-015-0517-6 [arXiv:1511.08361 [hep-ph]].
- [45] C. S. Fischer, A. Maas and J. M. Pawłowski, Annals Phys. **324** (2009) 2408 doi:10.1016/j.aop.2009.07.009 [arXiv:0810.1987 [hep-ph]].
- [46] A. Cucchieri and T. Mendes, PoS LAT **2007**, 297 (2007) [arXiv:0710.0412 [hep-lat]].
- [47] A. Cucchieri and T. Mendes, Phys. Rev. Lett. **100**, 241601 (2008) doi:10.1103/PhysRevLett.100.241601 [arXiv:0712.3517 [hep-lat]].
- [48] A. Cucchieri, D. Dudal, T. Mendes and N. Vandersickel, Phys. Rev. D **85** (2012) 094513 doi:10.1103/PhysRevD.85.094513 [arXiv:1111.2327 [hep-lat]].
- [49] O. Oliveira and P. J. Silva, Phys. Rev. D **86**, 114513 (2012) doi:10.1103/PhysRevD.86.114513 [arXiv:1207.3029 [hep-lat]].
- [50] R. F. Sobreiro and S. P. Sorella, JHEP **0506**, 054 (2005) [arXiv:hep-th/0506165].
- [51] A. C. Aguilar, D. Binosi and J. Papavassiliou, Phys. Rev. D **91**, no. 8, 085014 (2015) doi:10.1103/PhysRevD.91.085014 [arXiv:1501.07150 [hep-ph]].
- [52] M. Q. Huber, Phys. Rev. D **91**, no. 8, 085018 (2015) doi:10.1103/PhysRevD.91.085018 [arXiv:1502.04057 [hep-ph]].
- [53] M. A. L. Capri, A. D. Pereira, R. F. Sobreiro and S. P. Sorella, Eur. Phys. J. C **75**, no. 10, 479 (2015) doi:10.1140/epjc/s10052-015-3707-z [arXiv:1505.05467 [hep-th]].
- [54] M. A. L. Capri *et al.*, Phys. Rev. D **92**, no. 4, 045039 (2015) doi:10.1103/PhysRevD.92.045039 [arXiv:1506.06995 [hep-th]].
- [55] M. A. L. Capri *et al.*, Phys. Rev. D **93** (2016) no.6, 065019 doi:10.1103/PhysRevD.93.065019 [arXiv:1512.05833 [hep-th]].
- [56] M. A. L. Capri *et al.*, arXiv:1605.02610 [hep-th].
- [57] A. Cucchieri, T. Mendes and E. M. S. Santos, Phys. Rev. Lett. **103**, 141602 (2009) doi:10.1103/PhysRevLett.103.141602 [arXiv:0907.4138 [hep-lat]].
- [58] A. Cucchieri, T. Mendes, G. M. Nakamura and E. M. S. Santos, AIP Conf. Proc. **1354**, 45 (2011) doi:10.1063/1.3587584 [arXiv:1101.5080 [hep-lat]].
- [59] P. Bicudo, D. Binosi, N. Cardoso, O. Oliveira and P. J. Silva, Phys. Rev. D **92**, no. 11, 114514 (2015) doi:10.1103/PhysRevD.92.114514 [arXiv:1505.05897 [hep-lat]].
- [60] M. A. L. Capri, D. Fiorentini, M. S. Guimaraes, B. W. Mintz, L. F. Palhares and S. P. Sorella, arXiv:1606.06601 [hep-th].
- [61] M. Lavelle and D. McMullan, Phys. Rept. **279**, 1 (1997) [arXiv:hep-ph/9509344].
- [62] D. Zwanziger, Nucl. Phys. B **345**, 461 (1990).
- [63] R. Ferrari and A. Quadri, JHEP **0411**, 019 (2004) doi:10.1088/1126-6708/2004/11/019 [hep-th/0408168].
- [64] N. Dragon, T. Hurth and P. van Nieuwenhuizen, Nucl. Phys. Proc. Suppl. **56B**, 318 (1997) doi:10.1016/S0920-5632(97)00341-1 [hep-th/9703017].